How the Higgs Boson Was Found

Before the elusive particle could be discovered—a smashing success—it had to be imagined

By Brian Greene
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A famous story in the annals of physics tells of a 5-year-old Albert Einstein, sick in bed, receiving a toy compass from his father. The boy was both puzzled and mesmerized by the invisible forces at work, redirecting the compass needle to point north whenever its resting position was disturbed. That experience, Einstein would later say, convinced him that there was a deep hidden order to nature, and impelled him to spend his life trying to reveal it.

Although the story is more than a century old, the conundrum young Einstein encountered resonates with a key theme in contemporary physics, one that’s essential to the most important experimental achievement in the field of the last 50 years: the discovery, a year ago this July, of the Higgs boson.

Let me explain.

Science in general, and physics in particular, seek patterns. Stretch a spring twice as far, and feel twice the resistance. A pattern. Increase the volume an object occupies while keeping its mass fixed, and the higher it floats in water. A pattern. By carefully observing patterns, researchers uncover physical laws that can be expressed in the language of mathematical equations.

A clear pattern is also evident in the case of a compass: Move it and the needle points north again. I can imagine a young Einstein thinking there must be a general law stipulating that suspended metallic needles are pushed north. But no such law exists. When there is a magnetic field in a region, certain metallic objects experience a force that aligns them along the field’s direction, whatever that direction happens to be. And Earth’s magnetic field happens to point north.

The example is simple but the lesson profound. Nature’s patterns sometimes reflect two intertwined features: fundamental physical laws and environmental influences. It’s nature’s version of nature versus nurture. In the case of a compass, disentangling the two is not difficult. By manipulating it with a magnet, you readily conclude the magnet’s orientation determines the needle’s direction. But there can be other situations where environmental influences are so pervasive, and so beyond our ability to manipulate, it would be far more challenging to recognize their influence.

Physicists tell a parable about fish investigating the laws of physics but so habituated to their watery world they fail to consider its influence. The fish struggle mightily to explain the gentle swaying of plants as well as their own locomotion. The laws they ultimately find are complex and unwieldy. Then, one brilliant fish has a breakthrough. Maybe the complexity reflects simple fundamental laws acting themselves out in a complex environment—one that’s
filled with a viscous, incompressible and pervasive fluid: the ocean. At first, the insightful fish is ignored, even ridiculed. But slowly, the others, too, realize that their environment, its familiarity notwithstanding, has a significant impact on everything they observe.

Does the parable cut closer to home than we might have thought? Might there be other, subtle yet pervasive features of the environment that, so far, we’ve failed to properly fold into our understanding? The discovery of the Higgs particle by the Large Hadron Collider in Geneva has convinced physicists that the answer is a resounding yes.

Nearly a half-century ago, Peter Higgs and a handful of other physicists were trying to understand the origin of a basic physical feature: mass. You can think of mass as an object’s heft or, a little more precisely, as the resistance it offers to having its motion changed. Push on a freight train (or a feather) to increase its speed, and the resistance you feel reflects its mass. At a microscopic level, the freight train’s mass comes from its constituent molecules and atoms, which are themselves built from fundamental particles, electrons and quarks. But where do the masses of these and other fundamental particles come from?

When physicists in the 1960s modeled the behavior of these particles using equations rooted in quantum physics, they encountered a puzzle. If they imagined that the particles were all massless, then each term in the equations clicked into a perfectly symmetric pattern, like the tips of a perfect snowflake. And this symmetry was not just mathematically elegant. It explained patterns evident in the experimental data. But—and here’s the puzzle—physicists knew that the particles did have mass, and when they modified the equations to account for this fact, the mathematical harmony was spoiled. The equations became complex and unwieldy and, worse still, inconsistent.

What to do? Here’s the idea put forward by Higgs. Don’t shove the particles’ masses down the throat of the beautiful equations. Instead, keep the equations pristine and symmetric, but consider them operating within a peculiar environment. Imagine that all of space is uniformly filled with an invisible substance—now called the Higgs field—that exerts a drag force on particles when they accelerate through it. Push on a fundamental particle in an effort to increase its speed and, according to Higgs, you would feel this drag force as a resistance. Justifiably, you would interpret the resistance as the particle’s mass. For a mental toehold, think of a ping-pong ball submerged in water. When you push on the ping-pong ball, it will feel much more massive than it does outside of water. Its interaction with the watery environment has the effect of endowing it with mass. So with particles submerged in the Higgs field.

In 1964, Higgs submitted a paper to a prominent physics journal in which he formulated this idea mathematically. The paper was rejected. Not because it contained a technical error, but because the premise of an invisible something permeating space, interacting with particles to provide their mass, well, it all just seemed like heaps of overwrought speculation. The editors of the journal deemed it “of no obvious relevance to physics.”

But Higgs persevered (and his revised paper appeared later that year in another journal), and physicists who took the time to study the proposal gradually realized that his idea was a stroke of genius, one that allowed them to have their cake and eat it too. In Higgs’ scheme, the fundamental equations can retain their pristine form because the dirty work of providing the particles’ masses is relegated to the environment.

While I wasn’t around to witness the initial rejection of Higgs’ proposal in 1964 (well, I was around, but only barely), I can attest that by the mid-1980s, the assessment had changed. The physics community had, for the most part, fully bought into the idea that there was a Higgs field permeating space. In fact, in a graduate course I took that covered what’s known as the Standard Model of Particle Physics (the quantum equations physicists have assembled to describe the particles of matter and the dominant forces by which they influence each other), the professor presented the Higgs field with such certainty that for a long while I had no idea it had yet to be established experimentally. On occasion, that happens in physics. Mathematical equations can sometimes tell such a convincing tale, they can seemingly radiate reality so strongly, that they become entrenched in the vernacular of working physicists, even before there’s
data to confirm them.

But it's only with data that a link to reality can be forged. How can we test for the Higgs field? This is where the Large Hadron Collider (LHC) comes in. Winding its way hundreds of yards under Geneva, Switzerland, crossing the French border and back again, the LHC is a nearly 17-mile-long circular tunnel that serves as a racetrack for smashing together particles of matter. The LHC is surrounded by about 9,000 superconducting magnets, and is home to streaming hordes of protons, cycling around the tunnel in both directions, which the magnets accelerate to just shy of the speed of light. At such speeds, the protons whip around the tunnel about 11,000 times each second, and when directed by the magnets, engage in millions of collisions in the blink of an eye. The collisions, in turn, produce fireworks-like sprays of particles, which mammoth detectors capture and record.

One of the main motivations for the LHC, which cost on the order of $10 billion and involves thousands of scientists from dozens of countries, was to search for evidence for the Higgs field. The math showed that if the idea is right, if we are really immersed in an ocean of Higgs field, then the violent particle collisions should be able to jiggle the field, much as two colliding submarines would jiggle the water around them. And every so often, the jiggling should be just right to flick off a speck of the field—a tiny droplet of the Higgs ocean—which would appear as the long-sought Higgs particle.

The calculations also showed that the Higgs particle would be unstable, disintegrating into other particles in a minuscule fraction of a second. Within the maelstrom of colliding particles and billowing clouds of particulate debris, scientists armed with powerful computers would search for the Higgs' fingerprint—a pattern of decay products dictated by the equations.

In the early morning hours of July 4, 2012, I gathered with about 20 other stalwarts in a conference room at the Aspen Center for Physics to view the live-stream of a press conference at the Large Hadron Collider facilities in Geneva. About six months earlier, two independent teams of researchers charged with gathering and analyzing the LHC data had announced a strong indication that the Higgs particle had been found. The rumor now flying around the physics community was that the teams finally had sufficient evidence to stake a definitive claim. Coupled with the fact that Peter Higgs himself had been asked to make the trip to Geneva, there was ample motivation to stay up past 3 a.m. to hear the announcement live.

And as the world came to quickly learn, the evidence that the Higgs particle had been detected was strong enough to cross the threshold of discovery. With the Higgs particle now officially found, the audience in Geneva broke out into wild applause, as did our little group in Aspen, and no doubt dozens of similar gatherings around the globe. Peter Higgs wiped away a tear.

With a year of hindsight, and additional data that has only served to make the case for the Higgs stronger, here's how I would summarize the discovery's most important implications.

First, we've long known that there are invisible inhabitants in space. Radio and television waves. The Earth’s magnetic field. Gravitational fields. But none of these is permanent. None is unchanging. None is uniformly present throughout the universe. In this regard, the Higgs field is fundamentally different. We believe its value is the same on Earth as near Saturn, in the Orion Nebulae, throughout the Andromeda Galaxy and everywhere else. As far as we can tell, the Higgs field is indelibly imprinted on the spatial fabric.

Second, the Higgs particle represents a new form of matter, which had been widely anticipated for decades but had never been seen. Early in the 20th century, physicists realized that particles, in addition to their mass and electric charge, have a third defining feature: their spin. But unlike a child's top, a particle's spin is an intrinsic feature that doesn't change; it doesn't speed up or slow down over time. Electrons and quarks all have the same spin value, while
the spin of photons—particles of light—is twice that of electrons and quarks. The equations describing the Higgs particle showed that—unlike any other fundamental particle species—it should have no spin at all. Data from the Large Hadron Collider have now confirmed this.

Establishing the existence of a new form of matter is a rare achievement, but the result has resonance in another field: cosmology, the scientific study of how the entire universe began and developed into the form we now witness. For many years, cosmologists studying the Big Bang theory were stymied. They had pieced together a robust description of how the universe evolved from a split second after the beginning, but they were unable to give any insight into what drove space to start expanding in the first place. What force could have exerted such a powerful outward push? For all its success, the Big Bang theory left out the bang.

In the 1980s, a possible solution was discovered, one that rings a loud Higgsian bell. If a region of space is uniformly suffused with a field whose particulate constituents are spinless, then Einstein’s theory of gravity (the general theory of relativity) reveals that a powerful repulsive force can be generated—a bang, and a big one at that. Calculations showed that it was difficult to realize this idea with the Higgs field itself; the double duty of providing particle masses and fueling the bang proves a substantial burden. But insightful scientists realized that by positing a second “Higgs-like” field (possessing the same vanishing spin, but different mass and interactions), they could split the burden—one field for mass and the other for the repulsive push—and offer a compelling explanation of the bang. Because of this, for more than 30 years, theoretical physicists have been vigorously exploring cosmological theories in which such Higgs-like fields play an essential part. Thousands of journal articles have been written developing these ideas, and billions of dollars have been spent on deep space observations seeking—and finding—indirect evidence that these theories accurately describe our universe. The LHC’s confirmation that at least one such field actually exists thus puts a generation of cosmological theorizing on a far firmer foundation.

Finally, and perhaps most important, the discovery of the Higgs particle is an astonishing triumph of mathematics’ power to reveal the workings of the universe. It’s a story that’s been recapitulated in physics numerous times, but each new example thrills just the same. The possibility of black holes emerged from the mathematical analyses of German physicist Karl Schwarzschild; subsequent observations proved that black holes are real. Big Bang cosmology emerged from the mathematical analyses of Alexander Friedmann and also Georges Lemaître; subsequent observations proved this insight correct as well. The concept of anti-matter first emerged from the mathematical analyses of quantum physicist Paul Dirac; subsequent experiments showed that this idea, too, is right. These examples give a feel for what the great mathematical physicist Eugene Wigner meant when he spoke of the “unreasonable effectiveness of mathematics in describing the physical universe.” The Higgs field emerged from mathematical studies seeking a mechanism to endow particles with mass. And once again the math has come through with flying colors.

As a theoretical physicist myself, one of many dedicated to finding what Einstein called the “unified theory”—the deeply hidden connections between all of nature’s forces and matter that Einstein dreamed of, long after being hooked on physics by the mysterious workings of the compass—the discovery of the Higgs is especially gratifying. Our work is driven by mathematics, and has so far not made contact with experimental data. We are anxiously awaiting 2015 when an upgraded and yet more powerful LHC will be switched back on, as there’s a fighting chance that the new data will provide evidence that our theories are heading in the right direction. Major milestones would include the discovery of a class of hitherto unseen particles (called “supersymmetric” particles) that our equations predict, or hints of the wild possibility of spatial dimensions beyond the three we all experience. More exciting still would be the discovery of something completely unanticipated, sending us all scurrying back to our blackboards.

Many of us have been trying to scale these mathematical mountains for 30 years, some even longer. At times we’ve felt the unified theory was just beyond our fingertips, while at other times we’re truly groping in the dark. It is a great boost for our generation to witness the confirmation of the Higgs, to witness four-decade-old mathematical insights realized as pops and crackles in the LHC detectors. It reminds us to take the words of Nobel laureate Steven Weinberg to
heart: “Our mistake is not that we take our theories too seriously, but we do not take them seriously enough. It is always hard to realize that these numbers and equations we play with at our desks have something to do with the real world.” Sometimes, those numbers and equations have an uncanny, almost eerie ability to illuminate otherwise dark corners of reality. When they do, we get that much closer to grasping our place in the cosmos.

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